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Numerical Modeling of Shielding by a Wire Mesh Box

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Introduction

The rebar mesh in concrete walls often represents a primary means for shielding the inside of a building from fields due to lightning or other sources, or for preventing unintended radiation from sources in the building. Real situations can be very complicated, with the rebar mesh embedded in concrete and involving ground, grounding structures, apertures in the walls and conductors penetrating the walls. For this paper we consider the simple case of a plane wave incident on a wire mesh box to examine the effects of mesh parameters and evaluate the accuracy of the modeling codes for this application. The modeling was done with the NEC–4 moment method code, and also a FDTD code where the mesh box was modeled with rows of conducting cells, and a FDTD code coupled to a thin-wire model [1]. We also have looked at the effects of wires penetrating the mesh, a thin gap in the mesh, unbonded junctions and excitation by nearby currents rather than a plane wave.

In the next section we will briefly describe the numerical modeling methods used. Next, results are shown for a plane wave incident on a wire mesh box. The effect of varying the wire spacing, wire radius and frequency are demonstrated. Results from moment-method and FDTD codes are compared for validation, and the shielding is also compared with the analytic results developed by Casey [2].

Numerical Modeling Methods

Results for the mesh box were obtained by running a finite difference time domain (FDTD) code and a frequency domain moment method code NEC-4 [3]. Advantages of a moment method code such as NEC for modeling the mesh box are that wires can have arbitrary radius and location, and electric and magnetic fields can be computed at arbitrary locations near the structure. Also, the low frequency response can be obtained from one or a few frequency evaluations, while a time domain solution might need to be run for a long time period in order to extract the low frequencies from a Fourier transform.

A limitation of NEC for this application is that results become inaccurate when the spacing between wires in the mesh is less than several times the wire diameter. The error due to the thin-wire approximation will be demonstrated in our results. However, the conductor spacing for most rebar will probably be such that a thin-wire model will be suitable. Another limitation of NEC for modeling the mesh box is an instability that can occur with electrically small loops. The problem is seen as an erroneous loop current that grows as the inverse of frequency due to the moment-method matrix becoming ill-conditioned. Loop currents were seen in the mesh box at low frequencies, but did not appear to have a significant effect on the field evaluated at the center of the box.

The FDTD results for the box were obtained from a code using the Yee algorithm [4] with

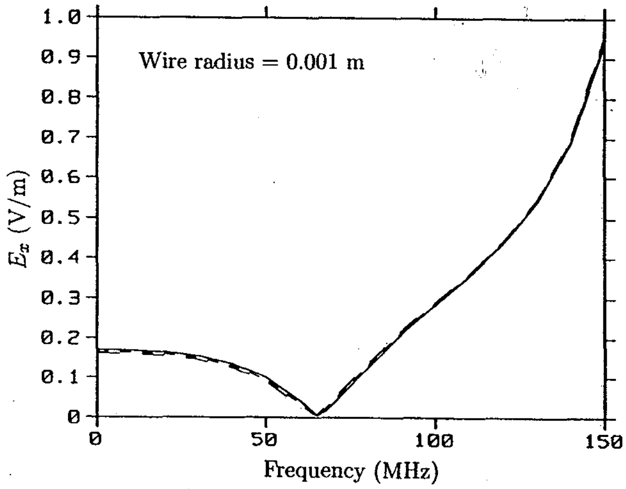

Fig. 1. Field at the center of a wire mesh box with 1 m side and five cells per side; NEC model with number of segments per mesh cell of 1 (solid), 2 (short dash) and 4 (long dash).

cubic cells and a PML absorbing boundary. It was found that a relatively thick PML region (12 cells) was needed to avoid reflections that would distort the low frequency response. The basic Yee algorithm is not well suited to modeling thin wires. A linear conductor can be represented with a string of highly conducting cells, but the diameter of the equivalent round wire is uncertain, but somewhat less than the cell width. We used this approach for modeling a mesh of thick wires where the NEC thin-wire model would not be accurate. To model wires thinner than the cell size we used the method described by Holland [1], in which transmission line differential equations representing the wire current and voltage are coupled to the equations for fields in the mesh. The box was excited with an incident plane wave having a Gaussian profile with full-width-half-max of about three times the width of the box. Shorter pulses would excite resonant modes in the box which would ring for a long time and were not of interest for the study of lightning effects. The solution was run for about 2000 time steps, and the response was then extended in time using the Generalized Pencil of Functions technique [5] until it had decayed to a very small value. The extended response was then Fourier transformed and deconvolved with the Gaussian pulse.

An error in loop currents similar to that seen in NEC was observed in the FDTD results for the mesh box. In the time domain it is manifest as a residual DC current in the loops that would flow forever after the actual response has decayed away. In a Fourier transform these DC currents would contribute an inverse frequency term at low frequencies as seen in NEC. This similarity to NEC could be expected, since the Yee algorithm expressed in integral form uses the field at the center of each edge to approximate the line integral of field around a face, similar to the point sampling in NEC.

Shielding by a Mesh Box

A box one meter on a side was chosen to study the shielding from a plane wave. Since NEC computes the scattered near field due to currents, the code had to be modified to add the incident plane wave field. The cancellation of incident and scattered fields will increase the relative error when shielding is high. The excitation in NEC was a plane wave of 1 V/m incident along the z axis with electric field in the x direction. The resulting E_x at the center of the box with 5 cells per side, and wire spacing of 0.2 m, is shown in Figure 1 for wire radii of 0.01 m and 0.001 m.

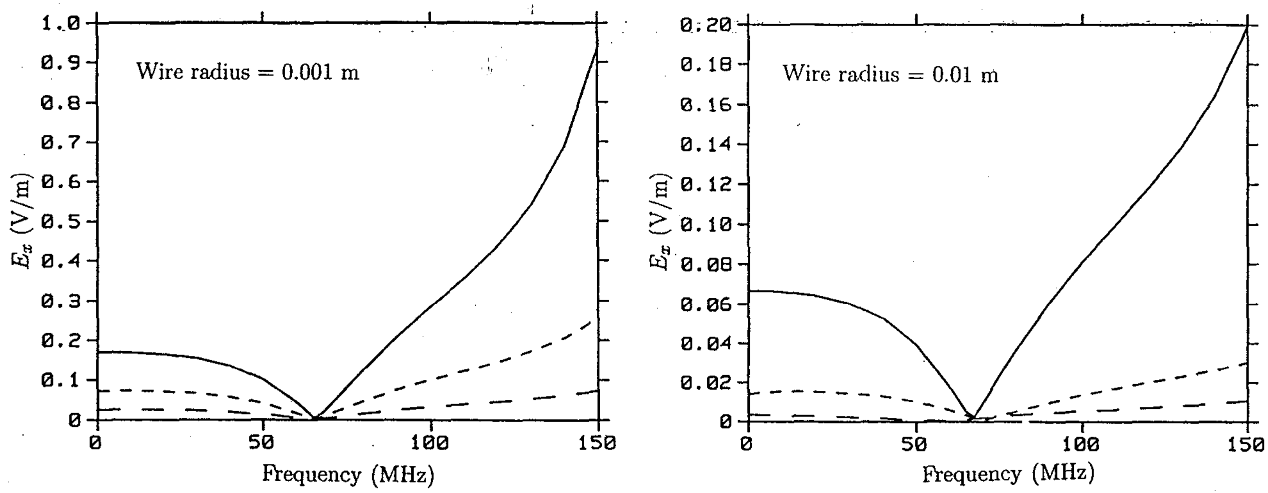

Fig. 2. NEC results for shielding by a 1 m mesh box with number of mesh cells per side of 5 (solid), 10 (short dash) and 21 (long dash).

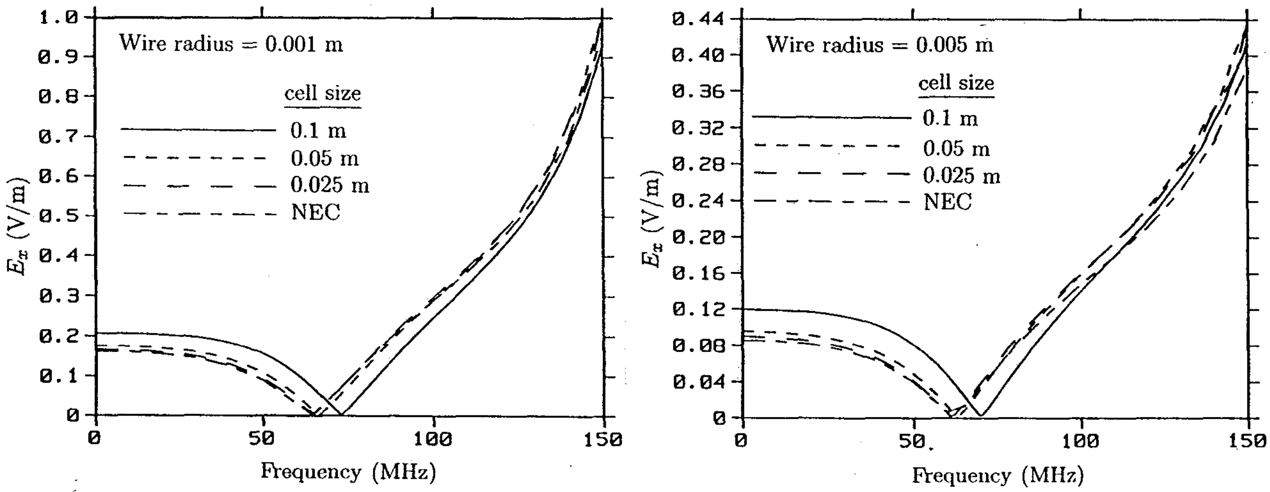

Fig. 3. FDTD solution for the field at the center of a wire mesh box with 1 m side and five mesh cells per side, using the thin-wire algorithm. The FDTD cell size was varied to test convergence.

In both cases the field is seen to remain relatively constant at low frequencies, then go into a null around 60 MHz and then begin rising as the electrical size of the mesh cells becomes larger. These NEC models were run with 1, 2 and 4 segments per side of each mesh opening (segment lengths of 0.2 m, 0.1 m and 0.05 m) to test the convergence of the solution. Convergence is good for a wire radius of 0.001 m, but more variation is seen for the 0.01 m radius due to the increased cancellation of fields. The field at the center of the 1 m box is shown in Figure 2 for 5, 10 and 21 mesh cells per side and wire radii of 0.001 m and 0.01 m. The reduced mesh size relative to the box size is seen to increase shielding, while shielding still becomes independent of mesh size relative to wavelength at low frequencies.

FDTD solutions for the same mesh box, with 1 m sides and five mesh cells per side, are shown in Figure 3. The thin-wire algorithm [1] was used to include the wires, and the FDTD cell size was varied from 0.1 m to 0.025 m to test convergence. NEC results using four segments per side of a mesh cell are included for comparison. The result for 0.1 m cells with a wire in every other cell are not too well converged, but the models with smaller cells compare well with NEC. The 0.01 m radius results are not shown, since the thin-wire FDTD algorithm became unstable with a cell size of 0.025 m. FDTD solutions in which wires were modeled by strings of highly conducting cells are shown in Figure 4. The wire spacing was 0.2 m in each case, with a wire in every fourth cell for 0.05 m cells (equivalent radius of about 0.02 m) and a wire in every eighth cell for 0.025 m cells (equivalent radius of about 0.01 m.) These results indicate that both NEC and FDTD algorithms are capable of modeling shielding by a mesh box, although relative error in the interior fields can be expected to increase as the shielding becomes more complete with increased conductor radius or increasing number of conductors in the walls.

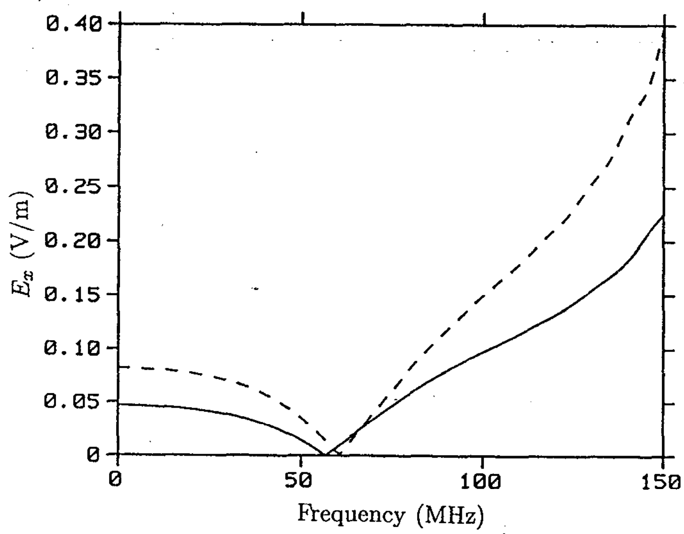

Fig. 4. FDTD solution for the field at the center of the mesh box with 1 m sides and five mesh cells per side. Wires were modeled as strings of conducting cells with a wire in every fourth cell with 0.05 m cells (solid) and in every eighth cell with 0.025 m cells (dashed).

The null that occurs around 57 MHz in the electric field at the center of the box is a characteristic feature of all of these results. The transfer function for field can be approximated as an inductance only at frequencies well above this null. This notch was also observed in the measurements made by Nyffeler et al. [6]. Since it occurs at too low a frequency to be associated with a resonant mode, it appears that it may be the result of interference between fields entering the box through different paths. To investigate this phenomena and attempt to get a better understanding of how the field enters the box, we tried modeling the box with some faces solid and some with mesh. The FDTD code was used with wires represented as strings of conducting cells, since with this code it is easy to make selected faces solid so that they are totally impenetrable by the field. A NEC mesh model will always have some leakage, even when the wire radius a and separation d are set for the "equal area" condition $2\pi a = d$. In the results here the term "TE faces" refers to the four faces on which the incident electric field is transverse to the face normal. "TM faces" refers to the other two faces where the incident H is transverse to the normal and E is normal to the face.

The modeling results showed that for frequencies from zero through 57 MHz the field entering through TM faces was nearly in phase with the phase of the incident field outside the box, while field entering through TE faces (mainly the face that the wave was incident on) had nearly constant phase through the box in the direction of the wave propagation. The interference of these fields produced the null on a plane across the center of the box. No null was seen away from the center position. The field entering the box through TM faces was dominant at low frequencies, and remained relatively constant to about 70 MHz. The field entering through TE faces increased approximately linearly with frequency, and exceeded the field from TM faces above about 57 MHz, so the null occurs when the two modes are equal and canceling. The null was seen in cubical boxes, but not when the box dimension parallel to the incident electric field is stretched to two or more times the other dimensions.

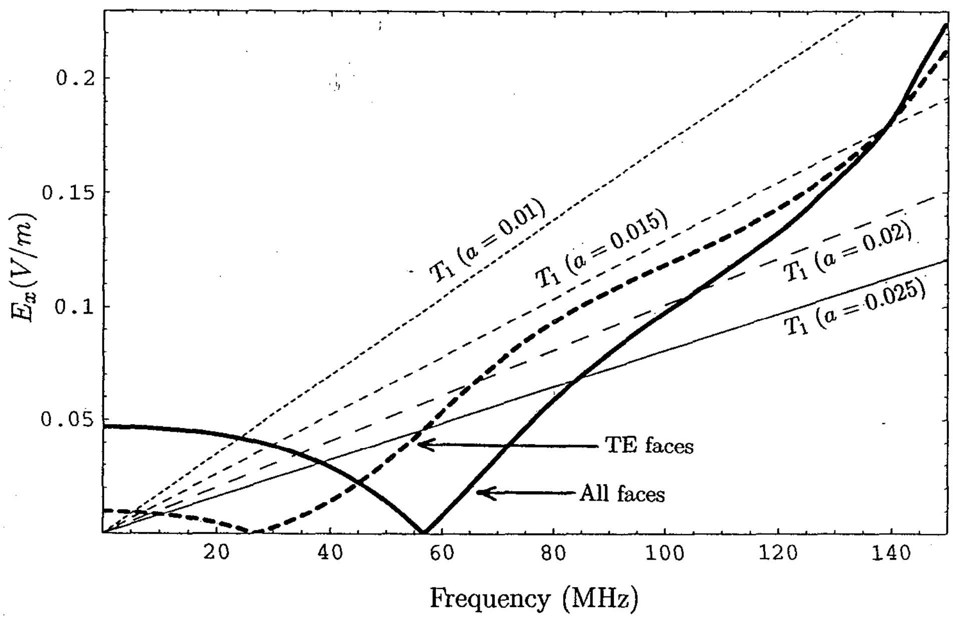

Fig. 5. Comparison of the transmission coefficient for normal incidence on an infinite mesh with the FDTD solution for a box with mesh on all sides and mesh on only the TE faces.

These numerical results were compared with analytic approximations derived by Casey [2] for the shielding by a wire mesh. Casey's results are based on a surface impedance operator derived from the space-averaged tangential electric field and space-averaged surface current density on the mesh. He applies this analysis to several cases, including a plane wave incident on an infinite mesh screen and quasistatic shielding by a mesh enclosure. For a plane wave incident normal to an infinite mesh, Casey's transmission coefficients reduce to

$$T_1 = \frac{d\mu_0\omega \log[(1 - e^{-2\pi a/d})^{-1}]}{\sqrt{(\pi\eta)^2 + \left[d\mu_0\omega \log[(1 - e^{-2\pi a/d})^{-1}]\right]^2}} \tag{1}$$

where d is the width of the square mesh cells and a is the wire radius. If the exponentials are replaced by two terms of their small argument approximation (1) reduces to

$$T_0 = \frac{d\mu_0\omega \log\left(\frac{d}{2\pi a}\right)}{\sqrt{(\pi\eta)^2 + \left[d\mu_0\omega \log\left(\frac{d}{2\pi a}\right)\right]^2}} \tag{2}$$

which is equivalent to the result derived by Lamb [7].

The transmission coefficient T_1 is compared in Figure 5 with FDTD results for the field at the center of the 1 m mesh box with 1 V/m wave incident normal to a face. In the FDTD model the wires were represented as strings of highly conducting cells with five openings per side of the box and a FDTD cell size of 0.05 m. Thus there were three free-space cells between wires, with the conductors spaced by four cells or d = 0.2 m. With strings of conducting cells, the radius of the equivalent round wire is somewhat uncertain but is expected to be in the range of 0.015 to 0.02 m for the 0.05 m cell size. In addition to the FDTD result for mesh on all sides of the box, Figure 5 includes the result for mesh on the four TE faces with the two TM faces solid. As expected, the result for mesh only on TE faces is in better agreement with T_1 than with mesh on all faces. The increasing slope of the numerical results above 140 MHz is the result of the cavity resonance which occurs around 206 MHz.

Casey's transmission coefficient T_1 and the simpler form T_0 are compared in Figure 6 with the numerical solution for a plane wave normally incident on an infinite, uniform mesh with $d = 0.2$ m and frequency of 30 MHz. The numerical results are from a 2D moment method solution using the thin-wire approximation for the infinite mesh. The boundary condition was matched on the wire axis. For the "A" result the current was located on the wire surface with a displacement transverse to the direction to the evaluation point, while for the "B" result the current was numerically integrated around the wire.

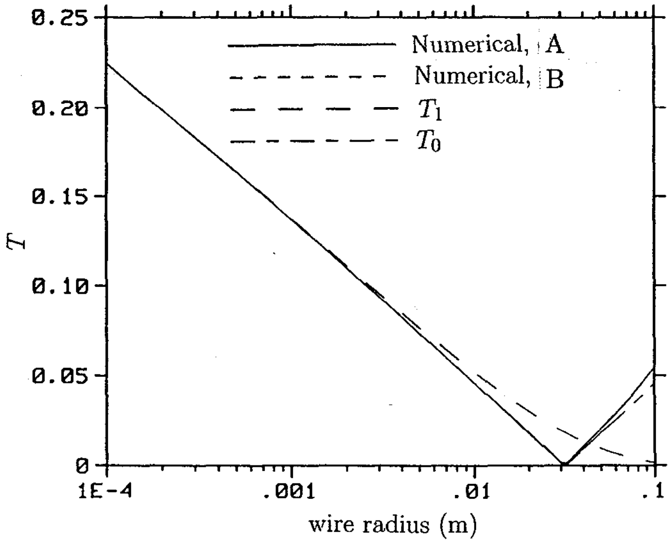

Fig. 6. Comparison of the transmission coefficients T_0 and T_1 for normal incidence on an infinite mesh with the numerical solution for an infinite screen of parallel wires with wire spacing 0.2 m and wire radius varied.

The electric field was evaluated at a distance 0.5 m behind the mesh, the same distance as the center of the 1 m box. All results are in agreement when wire radius a is much less than the wire spacing d. This agreement continued to hold as frequency was reduced to below 10 KHz, which indicates that the difference between the transmission coefficient and the field in the box is not due to near field effects. As the wire radius is increased, the numerical result goes into a null at $2\pi a = d$ and then increases for larger wire radius. Since the transmitted field should go to zero when the wires touch at $2a = d$, Casey's transmission coefficient is giving a credible result, while Lamb's approximation shows the same behavior as the thin-wire numerical models. This behavior of the thin-wire approximation to over estimate the shielding in the vicinity of $2\pi a = d$ is known as the "equal area rule" and is often used when it is desired to make a mesh represent a solid surface. However, in this case it represents an error in greatly over estimating the shielding.

Casey [2] also uses the surface impedance operator to derive expressions for shielding by wire mesh enclosures. He considers infinite parallel plates, a cylinder and a sphere, but the results for electrostatic shielding involve the enclosure shape only through the surface area and volume of the enclosure. For an enclosure with volume V_e and surface area S_e his result for the ratio of electrostatic field in the shielded region to field in the absence of the shield is

$$T_e = \left(1 + \frac{V_e}{l_e S_e}\right)^{-1} \qquad \text{where} \qquad l_e = \frac{d}{4\pi}\log[(1 - e^{-2\pi a/d})^{-1}]. \tag{3}$$

This result is compared with numerical results for the 1 m mesh box with $d = 0.2$ m in Figure 7. The numerical values up to a radius of 0.01 m were obtained with NEC for a frequency of 10 KHz. Since the NEC result for 0.01 m radius converged slowly, as seen in Figure 1, the values for one and four segments per side of the mesh cells are plotted in Figure 7. Also, the thin-wire approximation in NEC may over estimate the shielding for thick wires, as was seen in Figure 6.

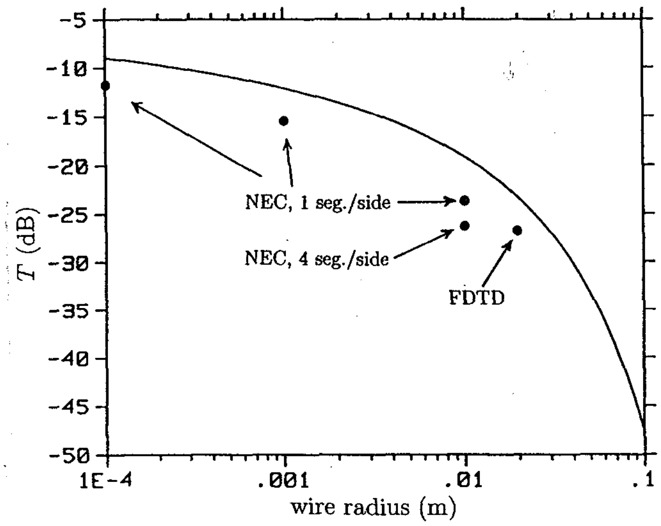

Fig. 7. Comparison of Casey's result for electrostatic shielding by an enclosure with the numerical solution for the mesh box for varying wire radius. Results for 0.01 m radius and less are from NEC and 0.02 m radius is FDTD.

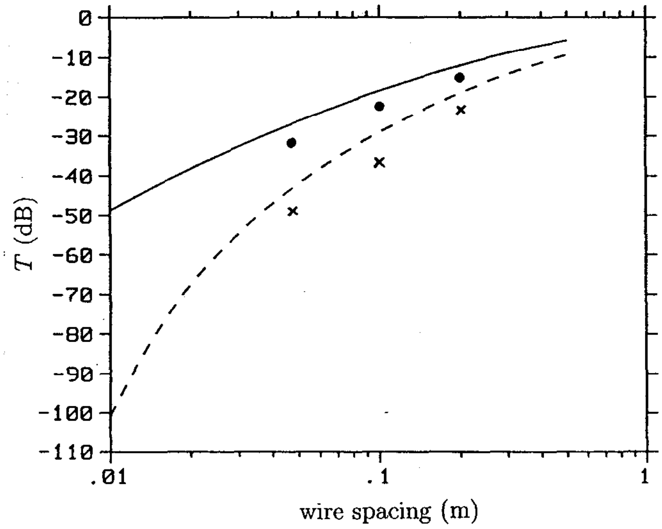

Fig. 8 Comparison of Casey's result for electrostatic shielding by an enclosure with the numerical solution for the mesh box for varying wire spacing. Solid line and dots are for a radius of 0.001 m, and dashed line and "x" are for a radius of 0.01 m.

The value plotted at 0.02 m radius in Figure 7 is from the FDTD code with a cell size of 0.05 m and wires modeled as strings of conducting cells. The numerical results show good agreement in trend with equation (3), although they are lower by about 3 dB. In Figure 8, NEC results for boxes with 5, 10 and 21 cells per side are compared with equation (3) for varying d and wire radii of 0.001 and 0.01 m. Again, the results agree in trend, but NEC results are about 3 dB lower than Casey's result.

Conclusion

Wire mesh cages were modeled using a thin-wire moment method code (NEC) and FDTD with either a thin wire algorithm or strings of conducting cells. All of these methods were found to be capable of giving accurate results for the shielding. When the conductor diameter was increased to about an eight to a quarter of the conductor spacing the FDTD code with conducting cells was the preferable method, since the thin-wire moment method over estimated the shielding while the thin-wire FDTD algorithm became unstable. As the shielding became more complete due to increased conductor diameter or number of conductors the error in the scattered field solution (NEC) increased and convergence became slow due to the cancellation of fields.

The shielding of the mesh cage was found to become independent of frequency for wavelengths much greater than five times the cage size, but continued to depend on the mesh size relative to cage size down to essentially zero frequency. For wavelengths less than about 1/5 of the cage size the field entering the cage increased roughly linearly until the cavity resonance was approached. The shielding was found to be predicted reasonably well by the plane wave transmission coefficient for higher frequencies (but below resonance). Low frequency shielding was in general agreement with Kendal Casey's result for electrostatic shielding by an enclosure, but the field in the box was about 3 dB less than Casey's result.

We also modeled mesh boxes modified with unbonded junctions, gaps and penetrating wires. An analytical result by Wait [8] showed greater shielding with unbonded junctions than with bonded junctions for an infinite mesh. There are also measurements that support this result [9]. However, the NEC model for the box showed no difference between unbonded and bonded junctions at low frequencies. With unbonded junctions on the 1 m box a resonance occurred around 60 MHz where the field in the box was a few dB above the field of the incident wave. From about 80 to 150 MHz there was again little difference. A thin gap encircling the top of the box on three sides also had little effect on field penetration at low frequencies but introduced a resonance around 50 MHz where the field inside was over 10 dB greater than the incident field. Of course, a gap completely encircling the box allowed field to enter down to low frequency. A wire penetrating into the cage without bonding to the mesh also allowed field to enter to low frequencies. When the wire was bonded to the mesh it increased the field in the cage by a smaller amount, but resulted in a large field penetration when either the interior or exterior parts of the wire were resonant.

Results of using wires to represent the lightning current showed that it is easy to introduce artifacts associated with resonances and charge concentrations on the 'lightning" wire that are not related to the actual lightning. More thought needs to be given to the way the lightning should be represented in a more complete model.

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References

[1] R. Holland, "Finite-Difference Analysis of EMP Coupling to Thin Struts and Wires," *IEEE Trans. Electromagnetic Compatibility*, v. EMC-23, no. 2, May 1981.

[2] K. F. Casey, "Electromagnetic Shielding Behavior of Wire-Mesh Screens," *IEEE Trans. on Electromagnetic Compat.*, vol. 30, no. 3, pp. 298-306, Aug. 1988.

[3] G. J. Burke, Numerical Electromagnetics Code — NEC–4, UCRL-MA-109338, Lawrence Livermore National Laboratory, CA, January 1992.

[4] K. S. Yee, "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media," *IEEE Trans. Antennas Propagat.*, Vol. AP-14, pp. 302-307, May 1966.

[5] T. K. Sarkar and O. Pereira, "Using the Matrix Pencil Method to Estimate the Parameters of a Sum of Complex Exponentials," *IEEE Antennas and Propagation Magazine*, Vol. 37, No. 1, February 1995.

[6] M. Nyffeler, B. Braendli, B. Reusser, E. Doerr, D. V. Giri and E. R. Tomer, "On the Interaction of Electromagnetic Fields with Wire Cage Structures," *IEEE Trans. on Electromagnetic Compat.*, vol. 34, no. 4, pp. 471-477, Nov. 1992.

[7] H. Lamb, "On the diffraction in transmission of electric waves by a metallic grating," *Proc. London Math. Soc.*, vol. 29, pp. 523-544, 1898.

[8] J. R. Wait, "Theories of Scattering from Wire Grid and Mesh Structures," in *Electromagnetic Scattering*, P. L. Uslenghi, Ed., New York, Academic Press, 1978, pp. 253-287.

[9] M. I. Kontrovich, V. Yu. Petrunikin, N. A. Yesepkina and M. I. Astrakhan, "The Coefficient of Reflection of a Plane Electromagnetic Wave from a Plane Wire Mesh," *Radio Engineering and Electron. Phys.*, vol. 2, pp. 222-231, 1962.